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Modelling regional input markets with numerous processing plants: The case of green maize for biogas production in Germany

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ABSTRACT

The location of first generation processing plants for biogas using bulky inputs is a prominent example of locational decisions of plants that face high per unit transport costs of feedstock and simultaneously depend to a large extent on feedstock availability. Modelling the resulting regional feedstock markets then requires a spatially explicit representation of demand. With production capacities of plants small in comparison to market size, large numbers of possible type-location combinations need to be considered, requiring considerable computation time under existing integer programming-based approaches. Therefore, in this paper we aim to present an alternative, faster and more flexible iterative solution approach to simulate location decisions for processing plants. And with greater flexibility, this approach is able to take into account spatially heterogeneous transport costs depending on total demand. The approach is implemented in a modelling framework for biogas production from green maize in Germany, which currently accounts for ca. five per cent of Germany's agricultural area. By modifying green maize prices, demand functions are derived and intersected with regional supply functions from an agricultural model to simulate market clearing prices and quantities. The application illustrates that our approach efficiently simulates markets characterised by small-scale demand units and high, spatially heterogeneous transport costs.

1. Introduction

The agricultural sector is rapidly being integrated into energy markets. Feedstock demand of first generation biofuels relies on existing market channels for cash crops such as cereals or oilseeds, and can therefore be integrated into existing economic simulation models for agriculture to assess social, economic and environmental impacts arising from changes in policies or markets (see e.g. Banse et al., 2008; Lampe, 2007; Hertel et al., 2008). Second generation biofuel production or first generation biogas production from agricultural biomass is however mainly based on bulky raw products with much higher per unit transport costs and small-scale, localised demand. The latter stems from location decisions for numerous bioenergy processing plants which are driven to a large degree by regional differences in transport and production costs of feedstock, especially if there is little spatial variance in other important factors such as output prices, investment costs and other operational costs. These location decisions in turn will drive regional markets for bioenergy feedstocks and interact with the market for cash crops, which calls for an integrated assessment of both types of markets. For an integrated assessment and modelling of policy settings in the agricultural and bioenergy sector, several interdisciplinary modelling approaches have been developed by combining quantitative models (see e.g. Janssen et al., 2009, van Delden et al., 2011; Viaggi et al., 2010) or by applying approaches based on geographical information systems (see e.g. Fiorese and Guariso, 2010).

In Germany, first generation biogas production from green maize and manure provides a prominent example for need of integrated assessments of policies. The so-called German Renewable Energy Act (EEG) supports the erection of biogas plants by implementing attractive feed-in tariffs for electricity produced by this type of source, guaranteed for 20 year and adjusted depending on manure shares, plant size and plant technology. The EEG, created in 1991 and reformed in 2004 and 2008 (BGBL, 2004), led to a sharp increase in electricity production from biogas and an increase in average plant sizes. The Agency for Renewable Resources estimates that 530,000 ha were used in 2009 to provide inputs for biogas production (FNR, 2009), accounting for about five percent of total agricultural land in

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Germany, or about 1/4 of what the EU subsidised in the past as renewable energy areas across the entire EU.

To the authors' knowledge, there is currently no tool available to simulate changes in feedstock demand and supply arising from this legislation or variants thereof. This paper therefore proposes a numerically feasible and efficient methodology to determine regional demand curves for agricultural bioenergy feedstock, which can then be integrated into existing impact assessment tools. It uses an iterative approach to determine maize and manure input demand for the most profitable plant at the most profitable locations first. Then, based on the remaining feedstock, demand for the next profitable plant is calculated, and so on. As a result, our approach does not imitate a social planner but rather replicates decentralised decisions under the assumption that the most profitable plants are opened first.[1] The approach is able to derive the number, locations and types of processing plants even if several thousands of possible combinations are under investigation for a region. Building on given regional supply curves for the feedstock, the methodology is applied to determine market clearing prices and quantities for biogas production from green maize and manure in Germany, based on the newly developed simulation tool ReSI-M (Regionalised Location Information System – Maize). Besides showing exemplary results for demand functions and regional market clearing quantities and prices, we provide detailed motivation for the chosen methodology, discuss underlying data and parameters and derive regional averages based on a sensitivity analysis for the key parameter "energy efficiency".

The paper is structured as follows: Section 2 provides the problem setting and relates it to relevant studies, motivating our choice of methodology. In Section 3 we describe the detailed methodology of ReSI-M. This is followed by Section 4 on the underlying data and its parameterisation. In Section 5, we discuss our approach with respect to the performance of the model, and finally, draw conclusion for the use of location models in the case of agricultural products with high transportation costs.

2. Problem setting, relevant studies and choice of methodology materials-methods

Our objective is to determine the total feedstock demand $d_r(w)$ for regions r at given feedstock demand prices w. For each region total demand $d_r(w)$ is derived by summing up over all plant types the plant type t specific feedstock demand x_t times their location-specific number $n_{r,t}(w)$:

$$d_r(w) = \sum_t n_{r,t}(w)x_t \tag{1}$$

The plant types are characterised by the given size and feedstock mix. The number of plants $n_{r,t}(w)$ of a specific type t erected at location r, at a given feedstock demand price w, depends on the operational profits $\pi_{r,t}$, defined as the difference between revenues - output y_t times price p_t – and the sum of operational costs net of feedstock costs oc_t, and feedstock costs. The latter are equal to the given input demand x_t multiplied by the sum of average per unit transport costs $\overline{tc_{r,t}}$ and feedstock price w.

$$\pi_{r,t} = y_t p_t - oc_t - x_t\left(\overline{tc_{r,t}} + w\right) \tag{2}$$

Average per unit transport costs $\overline{tc_{r,t}}$ are the outcome of a transport cost minimisation problems (see Section 3.1 below) which reflect inter alia regional availability of feedstock in the regions from where the feedstock is taken. Availability of feedstock depends on regionally differing "location factors". These are feedstock yields as well as the share of arable land on total land, the spatial distribution of this share and the amount of feedstock that is already used. This spatial distribution determines the homogeneity of a region.

[1] This approach allows for flexibility regarding the decision rule which determines plant types and plant locations. Besides different definitions of "most profitable" (i.e. based on absolute profits, profits per unit of investment, or introducing side conditions such as collateral necessary), stochastic rules, such as randomly choosing plants exceeding profitability thresholds, could also be used.

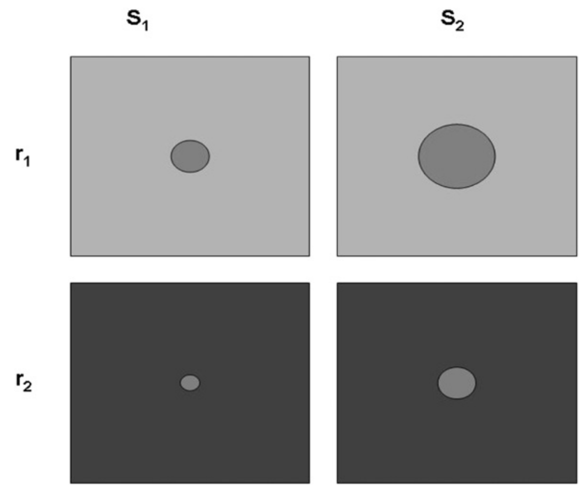

Fig. 1. Feedstock availability and related harvesting area.

In order to illustrate how location factors impact optimal plant size, Fig. 1 shows a hypothetical example with plants only differentiated by size, with two size classes s_1 and s_2 shown in the columns and two regions r_1 and r_2 in the rows. The intensity of the background colour relates to average feedstock availability of the regions, whereas the circles indicate the necessary harvest areas to feed the plants. Clearly, transport costs tc per unit of feedstock demand are higher in r_2 and for plant s_2. Accordingly, profits by plant size may be ranked differently in regions depending on feedstock availability. Equally, differences in regional feedstock prices may have an impact on the ranking.

However, as long as some feedstock is left, adding more plants would not change profitability for the different sizes, as the harvest area for each region, size and therefore transport costs are fixed. Total feedstock demand could simply be derived by first determining the most profitable plant size and then calculating the maximal number for that size possible from regional feedstock supply fs_r, at given feedstock price w. Unused regional feedstock quantities could then be eventually used for smaller sized plants with a lower profit.

For the problem at hand, feedstock demand per plant is small compared to maximal feedstock supply quantities fs_r, so that a large number of potential plants must be investigated. Moreover, data suggests that feedstock availability within the regions differs considerably, as shown by the grey gradient in Fig. 2. Accordingly, harvest areas vary within regions depending on feedstock density. Investors will now start to erect plants at such locations where feedstock availability is high and consequently transport costs low. Transport costs tc become a function of plants already erected. Our final problem setting adds complexity to Fig. 2 in that several regions are simulated together while allowing plants to acquire feedstock from any of them. Additionally, plants are also differentiated by feedstock shares and technology.

Existing literature (for an overview of methods used in location optimisation, see e.g.: Klose, 2001; Drezner and Hamacher, 2002; Klose and Drexl, 2005) does not directly offer a methodology to solve our problem setting efficiently. Classical solutions to combined location and capacity problems (cp. Aardal, 1998; Nagel, 2000; Melkote and Daskin, 2001) work with a distinct, pre-defined number of locations in space, and are solved as Mixed-Integer Linear Programming (LP) Problems in which per unit transport costs are given. Recent literature focusing on second generation biofuel plants stems from Leduc (2008) and (2010), and Kerdoncuff (2008) applies a Ware-House Location Problem with scenarios with given demands for bioenergy to determine an optimal location and size of biogas to liquid plants. Depending on the assumed demand and regional case study, resulting plant numbers are one to two in

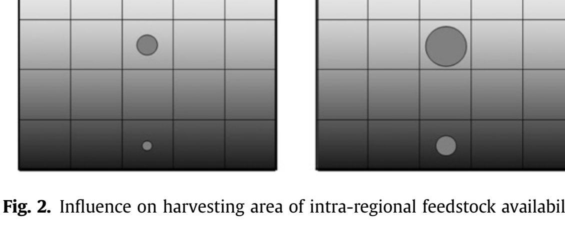

Fig. 2. Influence on harvesting area of intra-regional feedstock availability.